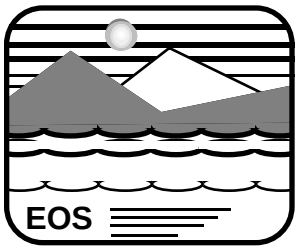


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# FLIGHT STAR CATALOG DEVELOPMENT FOR EOS-AM1

**P. Kudva**

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***McDONNELL DOUGLAS*** **- CSC - EER - CTA**

# FLIGHT STAR CATALOG DEVELOPMENT FOR EOS-AM1

## Introduction

The EOS-AM1 star catalog, a component of the onboard software, has been generated through a joint effort between FDD (Flight Dynamics Division) and the EOS-AM1 Project at the Goddard Space Flight Center. The process involved selection of 700 stars based on star magnitudes and their distribution in the catalog, from a 299433 star Master Catalog SKYMAP version 4.0a which was developed by FDD.

The spectral sensitivity curve, normalized relative to the maximum intensity, for the CT-601 star tracker lens/detector system was used to generate the instrument magnitudes for the Master Catalog stars. Since, the magnitude range for EOS-AM1 was specified as 2 through 5.7, all stars dimmer than magnitude 5.7 were eliminated, resulting in a catalog with 5213 stars. Simultaneously, based on selection criteria including magnitude range, near neighbor magnitude versus distance, proper motion, position and magnitude errors, a set of quality flags [1] were generated.

These flags, which quantified the quality of a star as a potential candidate for the Mission Catalog, were then used to reduce the 5213 star catalog to one with 1523 stars (Cat_1523). All the stars comprising the catalog Cat_1523 met the selection criteria for the EOS-AM1 mission. However, the 1523 stars exceeded the requirement of having no more than 700 stars in the catalog. The luxury afforded by the freedom to choose as a consequence of this excess was exploited to select a set of stars that had an equitable distribution while retaining most of the brighter stars.

The first step in selecting stars that were favorably distributed, was to identify a uniformly distributed set of points in the sky. Following the approach presented in [2], a set of 642 such points was then identified. This set was used both by FDD and the EOS-AM1 Project, each generating a 700 star catalog. The two catalogs were then judiciously combined, by eliminating some of the dimmer stars in close clusters, to arrive at the final version of the EOS-AM1 flight star catalog.

## Selection Parameters

### *Instrument Magnitude*

The magnitude range for EOS-AM1 was specified as 2 through 5.7. Since these correspond to the instrument magnitudes (i.e., as seen by the lens/detector system), the first step would be to convert the measured magnitudes of the Master Catalog stars to the corresponding instrument magnitudes. The magnitude sensed by a tracker is a function of the tracker sensitivity (the spectral response characteristics), the spectral type of the star being tracked and the spectral type of the star against which the tracker is calibrated. The spectral sensitivity curves, normalized relative to the maximum intensity, for the two star trackers 1 and 2 are shown in Fig. 1. In order to develop a single catalog for the two trackers, computation of the instrument magnitudes was based on a mean spectral sensitivity curve.

Also, the spectral type of the star against which the tracker is calibrated provides the zero-point for the instrument magnitudes. For EOS-AM1, this is G2V, so that the color index, which is the difference between the visual magnitude of a star and the magnitude sensed by the instrument, for G2V type stars was set to zero.

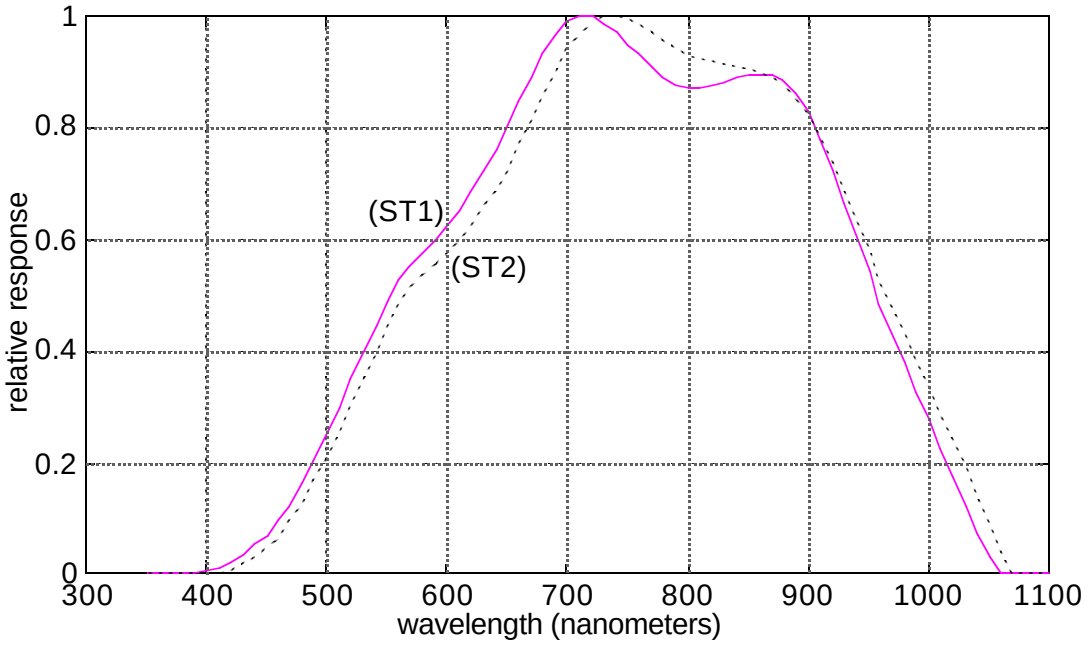


**Fig. 1 : Comparison of ST1 and ST2 Spectral Responses**

***Other parameters***

The following criteria were used to include stars for the mission catalog:

- variable V amplitude < 0.1 magnitude
- for a component of a multiple star, nearest star is not less than 5 magnitudes (MAGNIT3*) dimmer, or is less than 5 arcseconds (SENRES*) away
- position knowledge error < 0.25 arcseconds
- predicted magnitude knowledge error < 0.25 magnitudes
- a near neighbor star within 0.2 degrees must be dimmer by at least 5 magnitudes (MAGNIT7*)
- a near neighbor star within 0.6 degrees must have a magnitude difference of at least 0.75 magnitudes (MAGNIT8*)
- total proper motion 0.7 arcseconds/year

## Steps in the Flight Star Catalog Development

***Step 1***

The initial processing of the SKYMAP Master Catalog was performed by FDD using the MMSCAT program (SKYMAP standard software) [1]. In addition to generating a 5213 star catalog with the color corrected instrument magnitudes, MMSCAT simultaneously computes a set of quality flags for the stars in this catalog. This catalog excluded all stars with instrument magnitudes dimmer than magnitude 5.7.

A brief description of the quality flags is given in Table 1. Assignment of numerical values to these flags for each star, is facilitated by the definitions contained in Tables 2 and 3 of Appendix I.

* Nomenclature used in Tables 1 - 3

| Flag* # | Name | Description | Criterion for star inclusion |
|---|---|---|---|
| 1 | variability | maps amplitude variations | V amplitude < 0.1 |
| 3 | multiplicity | maps magnitude differences of known multiple stars - if the star is a component of a multiple star, nearest star is not less than MAGNIT3 magnitudes dimmer, or is less than SENRES (5 arcseconds) away [SENRES is the minimum distance between two stars that the sensor can resolve: stars separated by less than SENRES will be blended together. Thus, SENRES is used to decide when two stars need to be combined together] | nearest star is greater than 5 magnitudes dimmer or is less than 5 arcseconds away |
| 5 | position knowledge error | maps position errors in arcseconds | position knowledge error < 0.25 arcsecs. |
| 6 | predicted magnitude knowledge error | maps error in predicted instrument magnitudes | predicted magnitude knowledge error < 0.25 mags |
| 7 | near-neighbor | maps angle (degrees) to the nearest star that is either brighter than or up to MAGNIT7 magnitudes dimmer | star within 0.2 degs. should be dimmer by at least 5 (MAGNIT7) mags. |
| 8 | near-neighbor | maps angle (degrees) to the nearest star that is within MAGNIT8 magnitudes either dimmer or brighter | star within 0.6 degs. should have a magnitude difference of at least 0.75 (MAGNIT8) mags. |

* Flags not used in the development of the EOS-AM1 star catalog are not listed here

**Table 1 : Description of Quality Flags**

***Step 2***

The quality flags were then processed using the numerical values contained in Table 3. In particular, using the parameters mentioned earlier, stars with the following quality flag values were selected:

Qual_Flag_1 = 0
Qual_Flag_3 < 2
Qual_Flag_5 = 0
Qual_Flag_6 = 0
Qual_Flag_7 < 10
Qual_Flag_8 < 10

Of the selected stars, only those were retained whose

- instrument magnitudes were in the range +2 through +5.7, and
- whose proper motion was less than 0.7 arcseconds per year.

This resulted in a catalog of 1523 stars (Cat_1523).

***Step 3***

While all the 1523 stars comprising the catalog Cat_1523 met the selection criteria for the flight catalog, the choice had to be restricted to the *best* 700 stars. The term 'best' is used here to represent a set of stars that are equitably distributed in the celestial sphere while retaining the brighter stars. This is facilitated by the identification of a uniformly distributed set of points in the sky that could serve as a reference.

This was done by the approach presented in [2] which involves the following sequence:

- consider a regular icosahedron (a polyhedron with 20 faces, each of which is an equilateral triangle) inscribed in the celestial sphere
- each face is then divided into $N^2$ equilateral triangles, N across each side
- selecting the vertices ( a total of $10\ N^2 +2$) of all these smaller triangles to serve as a uniformly distributed set of points in the sky

The number of vertices is 642 with N = 8 and is 812 with N = 9. Since a number closer to 700 was desired, N = 8 was used to generate a set of 642 uniformly distributed points.

The EOS-AM1 Project and FDD used different approaches to generate the 'best' set of 700 stars based on this 642 point reference in the celestial sphere. These approaches are discussed in the following.

***Step 4a (EOS-AM1 Project)***

Each star in Cat_1523 was indexed to the vertex (among the 642) closest to it. This led to the assignment of the 1523 stars to only 576 vertices, leaving 66 in the star poor regions unassigned. For each of these 576 vertices, the brightest star in its vicinity was chosen. This process was repeated a second time, by indexing each of the remaining 947 (= 1523 - 576) stars of Cat_1523 with the vertex (among the remaining 66) closest to it. This time, 65 more vertices were assigned, each to a Cat_1523 star, leaving just one vertex unassigned and for each vertex, the star closest to it was chosen, leading to a set of 641 stars. The star closest to the remaining vertex was then added, resulting in an intermediate catalog of 642 stars. An assessment made of the distance between each vertex and the star associated with it resulted in the following statistics:

$$\text{Min} \rightarrow 0.23^{o};\ \text{Max} \rightarrow 10.67^{o};\ \text{Mean} \rightarrow 3.45^{o}$$

In order to fill in the remaining 58 stars, 58 vertices in the star poor regions were selected. Of the remaining 881 stars of Cat_1523, the one closest to each of these 58 vertices were added on to the intermediate catalog. These 58 stars additional stars resulted in a catalog of 700 stars (Cat_EOS).

***Step 4b (FDD)***

The star catalog should not only contain a set of well distributed stars, it would be desirable to retain as many of the brighter stars as possible. In order to combine the features of separation distance

(of a star from a vertex) and the magnitude (or intensity*), FDD used the following index of performance:

$$J = \textit{separation distance} / (\textit{intensity})^{0.3333}$$

Starting with the first of the 642 vertices, the member of Cat_1523 with the minimum value of J was selected. By sequentially going through each vertex, a star was selected from the remaining members of Cat_1523. Once a set 642 stars was thus chosen, the brightest 58 of the remaining 881 stars from Cat_1523 were added to that set to give a 700 star catalog (Cat_FDD).

***Step 5***

As may be expected, these two approaches did not result in an identical set of 700 stars - in fact, the two catalogs, Cat_EOS and Cat_FDD had only 488 stars in common. A comparison of the two catalogs was conducted in terms of the magnitudes and the near-neighbor separation of the member stars as presented in Figs. 2 through 4.

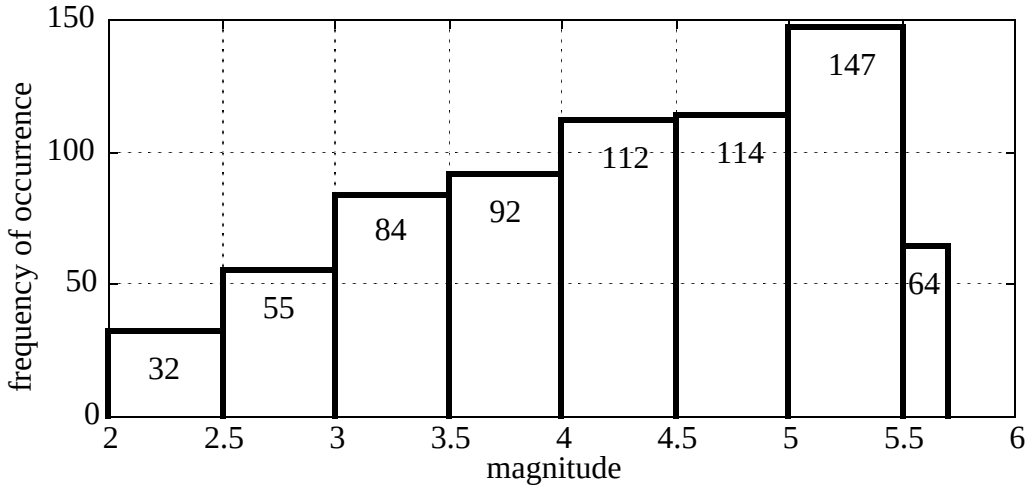


**Fig. 2(a) : Magnitude Histogram for Cat_EOS**

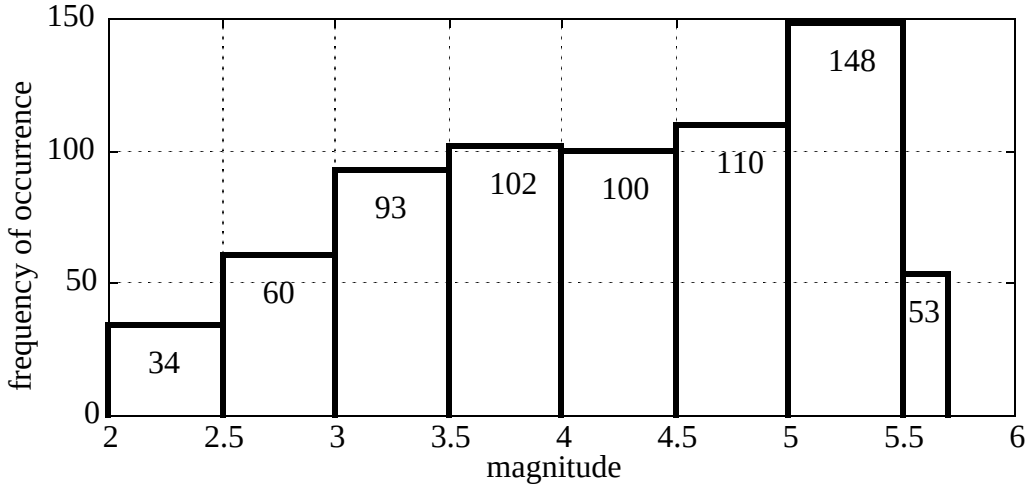


**Fig. 2(b) : Magnitude Histogram for Cat_FDD**

* Star intensity is related to its magnitude by the relation: *magnitude* = - 2.5 $\log_{10}$ (*intensity*)

Cat_FDD has a superior magnitude distribution (Fig. 2), since it contains a brighter set of stars than Cat_EOS. In terms of the near-neighbor separation, however, both catalogs are comparable (Fig. 3).

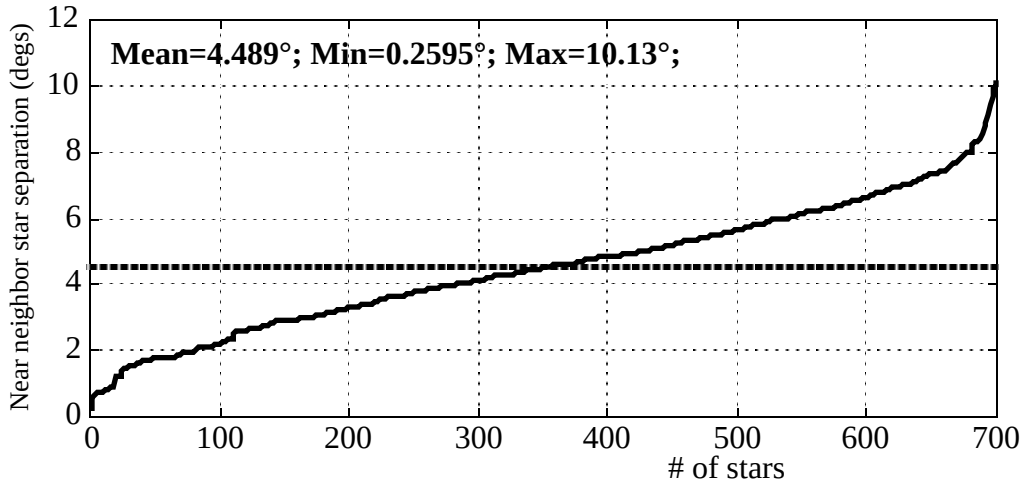


**Fig. 3(a) : Near-neighbor separation for the stars in Cat_EOS**

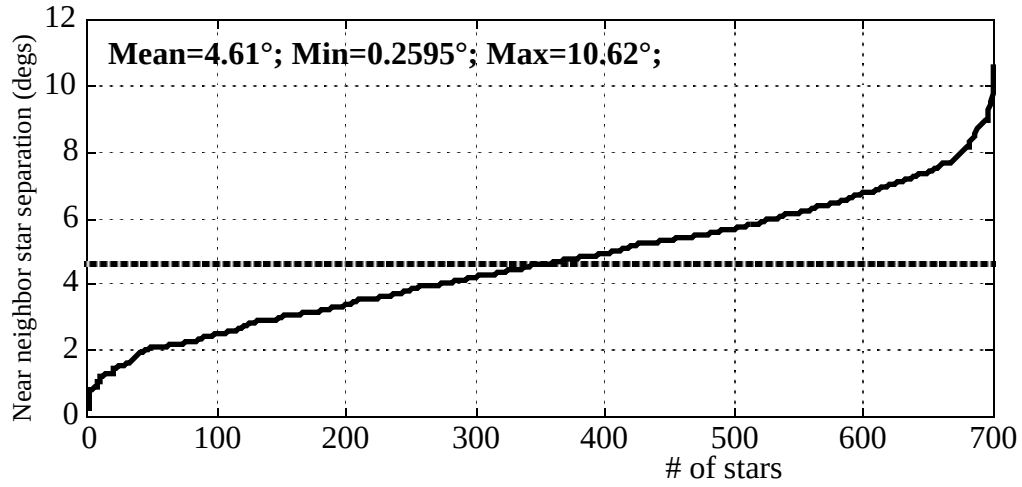


**Fig. 3(b) : Near-neighbor separation for the stars in Cat_FDD**

The distribution of the catalog stars in the sky, for both Cat_EOS and Cat_FDD, is presented in a sinusoidal projection in Figs. 4(a) and Fig. 4(b). Both these figures indicate the presence of close clusters of stars in some, but not necessarily the same, regions of the sky. As discussed below, elimination of dimmer stars from some of these clusters, allowed the two catalogs to be combined to a final set of 700 stars.

***Step 6***

The two catalogs, Cat_EOS and Cat_FDD, were combined retaining only one set of the 488 stars in common to both catalogs. This generated a catalog of 912 distinct stars. The catalog development process was now reduced to removing 212 stars from this intermediate catalog.

The 912 stars of this catalog were sorted in order of increasing brightness. Starting with the dimmest member, the near-neighbor separation for each of these stars with the closest ***brighter*** neighbor was tabulated. The 212 stars with the smallest such near-neighbor separation were then eliminated to arrive at the final 700 star catalog, Cat_EOS-AM1.

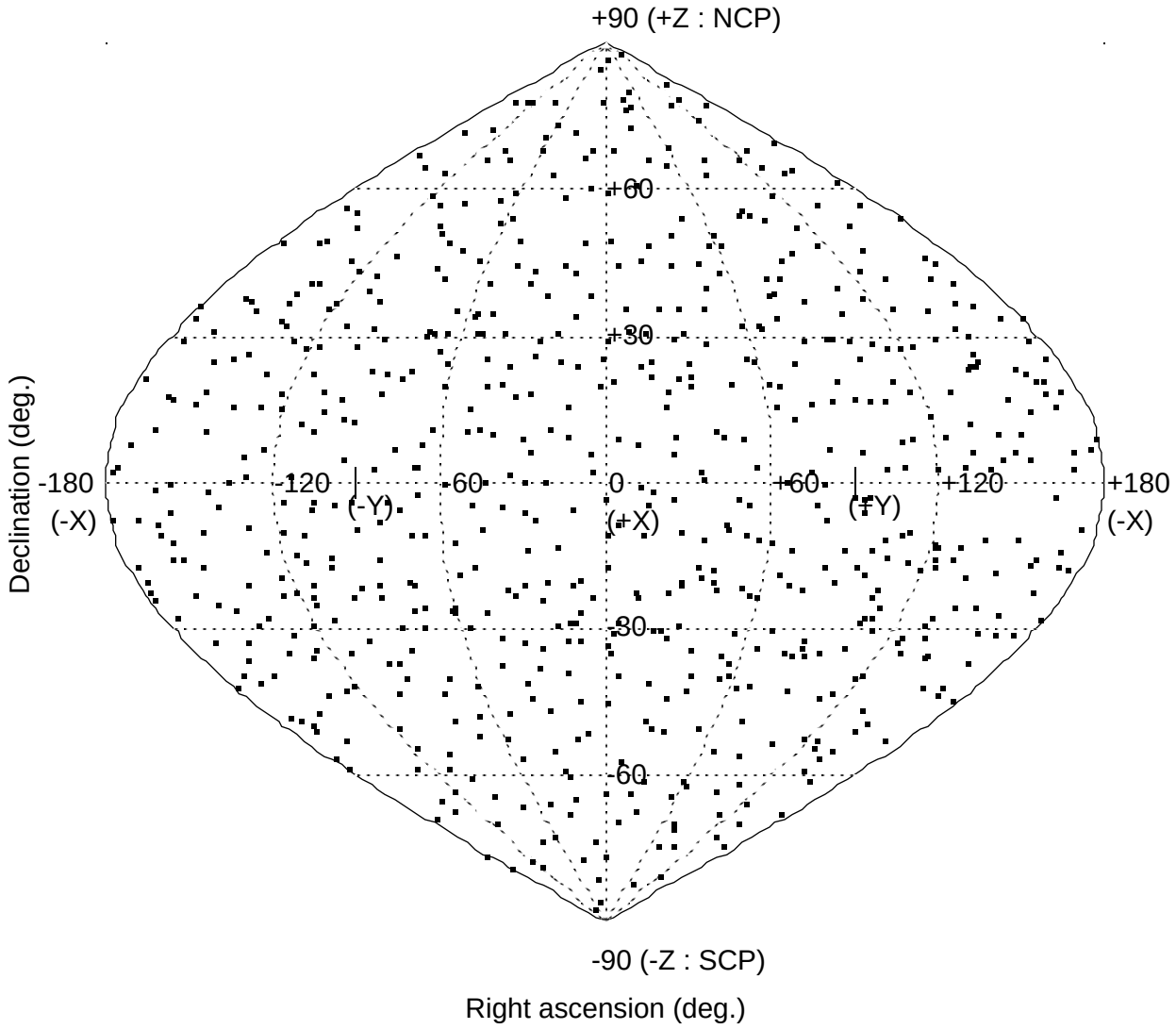


**Fig. 4(a) : Cat_EOS Star distribution (sinusoidal projection)**

## The Flight Star Catalog - a brief discussion

The magnitude histogram for the stars contained in Cat_EOS-AM1 (Fig. 5(a)) indicates an acceptable magnitude distribution. An examination of the magnitude profile of the 212 stars that were dropped (Fig. 5(b)) shows that a few of the brighter stars were eliminated in the process. However, this was a result of each of these bright stars having a ***brighter*** star in its vicinity, thus reducing the likelihood of star misidentification.

A plot of the near-neighbor separation between the members of Cat_EOS-AM1 is given in Fig. 6. The minimum separation has moved from a quarter of a degree for either of the two parent catalogs, Cat_EOS and Cat_FDD, up to about 3.2°, while the mean separation has edged up to about 5°. This shows that the elimination of some of the dimmer stars from the clusters has been accomplished while retaining the desirable stellar distribution feature of the resulting catalog. This is further illustrated in Fig. 7 which shows the distribution of the catalog stars in the sky, for Cat_EOS-AM1.

The relevant information of the member stars of Cat_EOS-AM1 (the components of the star unit vector in the mean J2000 ECI frame, its instrument magnitude and its SKYMAP number) is given in Appendix II.

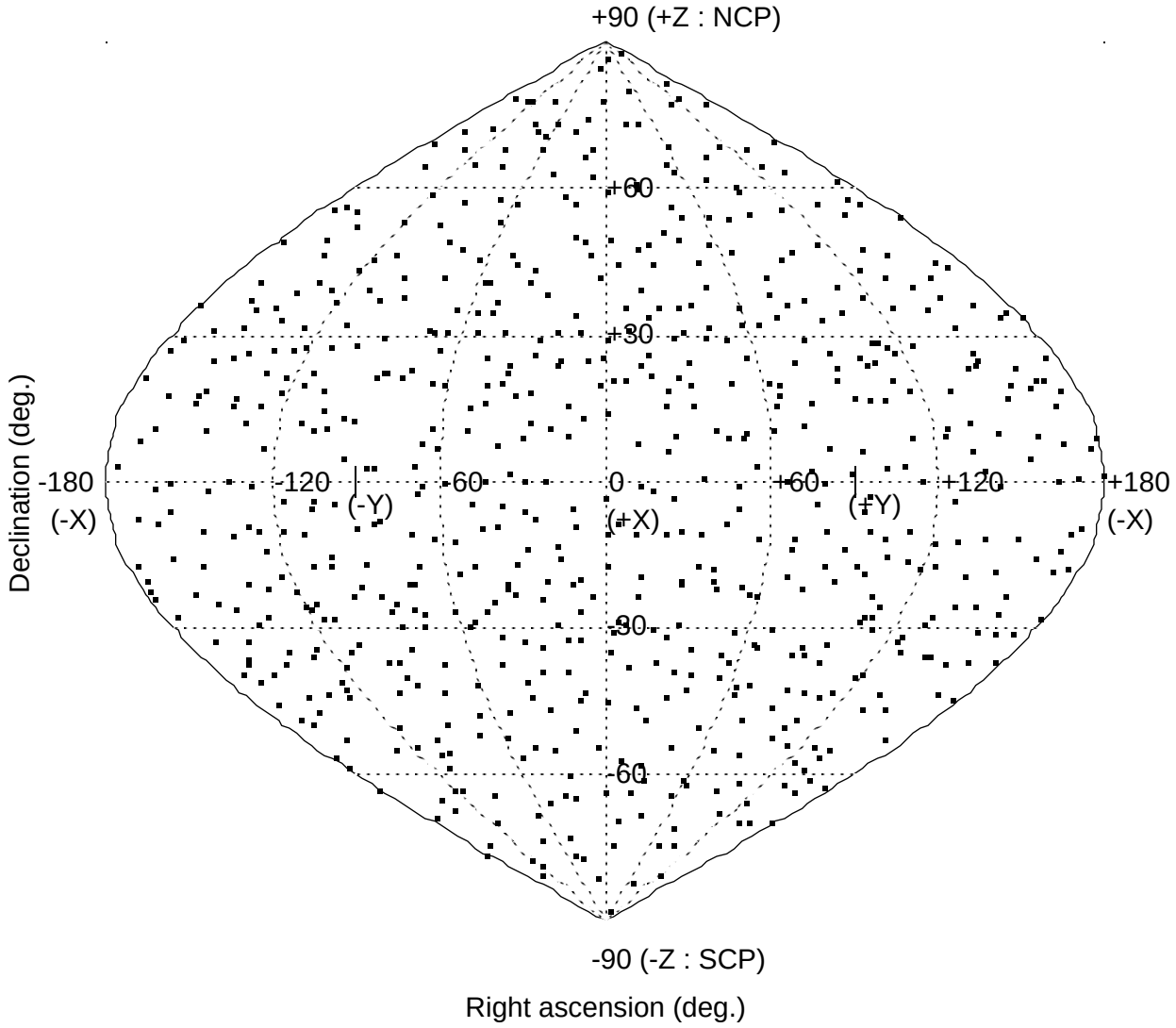


**Fig. 4(b) : Cat_FDD Star distribution (sinusoidal projection)**

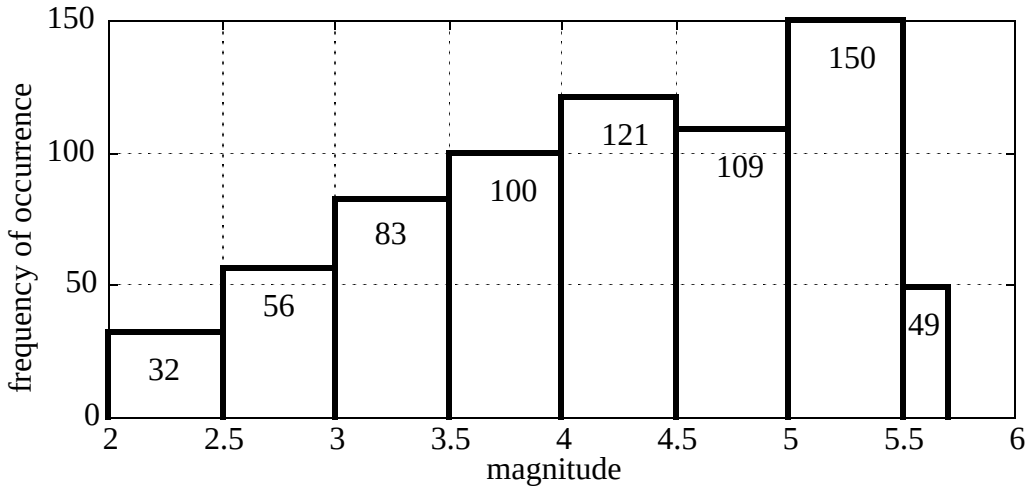


**Fig. 5(a) : Magnitude Histogram for Cat_EOS-AM1**

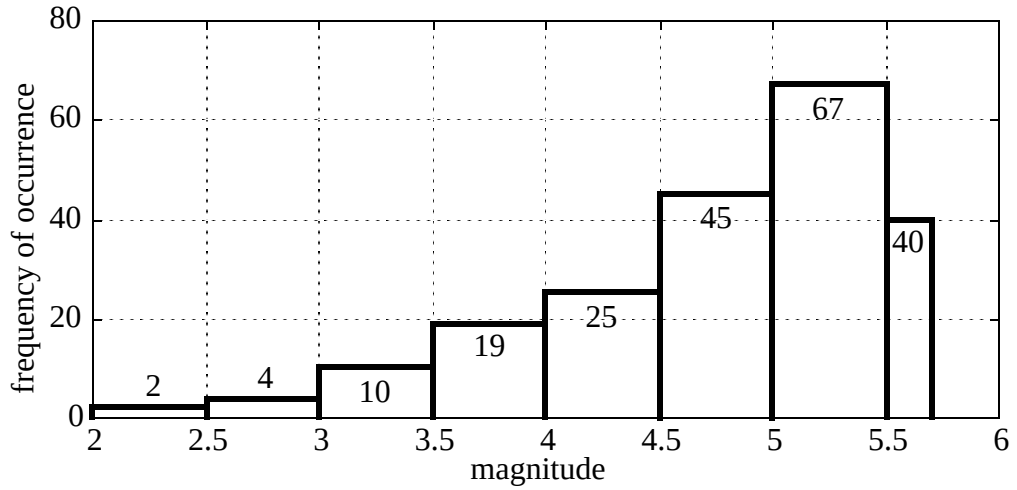


**Fig. 5(b) : Magnitude histogram for the 212 dropped stars from Cat_EOS and Cat_FDD**

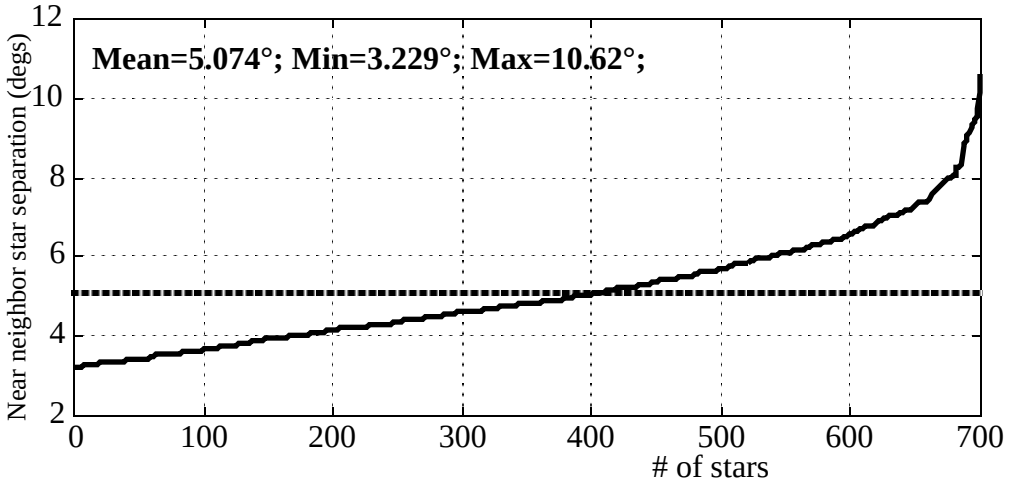


**Fig. 6 : Near-neighbor separation for the stars in Cat_EOS-AM1**

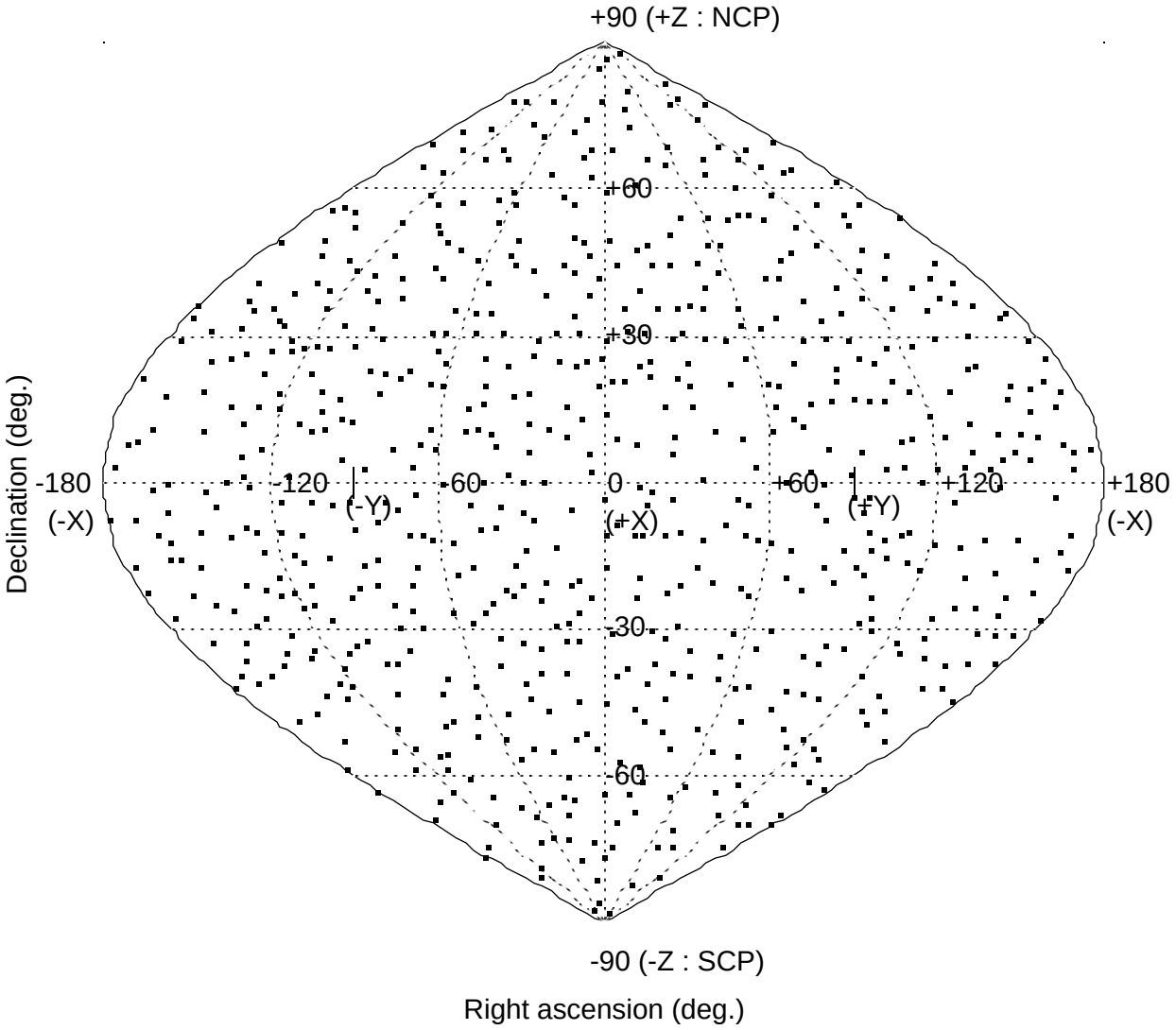


**Fig. 7 : Cat_EOS-AM1 Star distribution (sinusoidal projection)**

## References

1. "SKYMAP System Users Guide - Rev. 3", FDD Report # 553-FDD091 / 100R3UD0.

2. E. A. Ketchum and R. H. Tolson, "Lost in Space: Onboard Star Identification using CCD Star Tracker Data Without an A-Priori Attitude", Paper AAS 93-326, 1993.

# APPENDIX I

## QUALITY FLAG DEFINITIONS

| Flag Value | Definition |
|---|---|
| 0 | QLFLG1 (1) ≤ amplitude < QLFLG1 (2) |
| 1 | QLFLG1 (2) ≤ amplitude < QLFLG1 (3) |
| 2 | QLFLG1 (3) ≤ amplitude < QLFLG1 (4) |
| 3 | QLFLG1 (4) ≤ amplitude < QLFLG1 (5) |
| 4 | QLFLG1 (5) ≤ amplitude < QLFLG1 (6) |
| 5 | QLFLG1 (6) ≤ amplitude < QLFLG1 (7) |
| 6 | QLFLG1 (7) ≤ amplitude < QLFLG1 (8) |
| 7 | QLFLG1 (8) ≤ amplitude < QLFLG1 (9) |
| 8 | QLFLG1 (9) ≤ amplitude < QLFLG1 (10) |
| 9 | QLFLG1 (10) ≤ amplitude < QLFLG1 (11) |
| 10 | QLFLG1 (11) ≤ amplitude < QLFLG1 (12) |
| 11 | QLFLG1 (12) ≤ amplitude < QLFLG1 (13) |
| 12 | QLFLG1 (13) ≤ amplitude < QLFLG1 (14) |
| 13 | QLFLG1 (14) ≤ amplitude < QLFLG1 (15) |
| 14 | amplitude ≥ QLFLG1 (15) |
| 15 | known variable with unknown amplitude |

**Table - 2a : Quality Flag 1 Definition**

| Flag Value | Definition |
|---|---|
| 0 | Not a multiple star or multiple star treated as a near-neighbor |
| 1 | Nearest star is either greater than or equal to MAGNIT3 magnitudes dimmer, or is less than SENRES arcseconds away, or if definition of flags 0 or 2-7 does not apply |
| 2 | QLFLG3 (5) ≤ magnitude difference < QLFLG3 (6) = MAGNIT3 |
| 3 | QLFLG3 (4) ≤ magnitude difference < QLFLG3 (5) |
| 4 | QLFLG3 (3) ≤ magnitude difference < QLFLG3 (4) |
| 5 | QLFLG3 (2) ≤ magnitude difference < QLFLG3 (3) |
| 6 | QLFLG3 (1) ≤ magnitude difference < QLFLG3 (2) |
| 7 | magnitude difference < QLFLG3 (1) |

**Table - 2b : Quality Flag 3 Definition**

| Flag Value | Definition |
|---|---|
| 0 | QLFLG5 (1) ≤ position measurement error < QLFLG5 (2) |
| 1 | QLFLG5 (2) ≤ position measurement error < QLFLG5 (3) |
| 2 | QLFLG5 (3) ≤ position measurement error < QLFLG5 (4) |
| 3 | QLFLG5 (4) ≤ position measurement error < QLFLG5 (5) |
| 4 | position measurement error ≥ QLFLG5 (5) |

**Table - 2c : Quality Flag 5 Definition**

| Flag Value | Definition |
|---|---|
| 0 | QLFLG6 (1) ≤ magnitude error < QLFLG6 (2) |
| 1 | QLFLG6 (2) ≤ magnitude error < QLFLG6 (3) |
| 2 | QLFLG6 (3) ≤ magnitude error < QLFLG6 (4) |
| 3 | QLFLG6 (4) ≤ magnitude error < QLFLG6 (5) |
| 4 | QLFLG6 (5) ≤ magnitude error < QLFLG6 (6) |
| 5 | magnitude error ≥ QLFLG6 (6) |

**Table - 2d : Quality Flag 6 Definition**

| Flag Value | Definition |
|---|---|
| 0 | near-neighbor distance ≥ QLFLG7 (1) |
| 1 | QLFLG7 (2) ≤ near-neighbor distance < QLFLG7 (1) |
| 2 | QLFLG7 (3) ≤ near-neighbor distance < QLFLG7 (2) |
| 3 | QLFLG7 (4) ≤ near-neighbor distance < QLFLG7 (3) |
| 4 | QLFLG7 (5) ≤ near-neighbor distance < QLFLG7 (4) |
| 5 | QLFLG7 (6) ≤ near-neighbor distance < QLFLG7 (5) |
| 6 | QLFLG7 (7) ≤ near-neighbor distance < QLFLG7 (6) |
| 7 | QLFLG7 (8) ≤ near-neighbor distance < QLFLG7 (7) |
| 8 | QLFLG7 (9) ≤ near-neighbor distance < QLFLG7 (8) |
| 9 | QLFLG7 (10) ≤ near-neighbor distance < QLFLG7 (9) |
| 10 | QLFLG7 (11) ≤ near-neighbor distance < QLFLG7 (10) |
| 11 | QLFLG7 (12) ≤ near-neighbor distance < QLFLG7 (11) |
| 12 | QLFLG7 (13) ≤ near-neighbor distance < QLFLG7 (12) |
| 13 | QLFLG7 (14) ≤ near-neighbor distance < QLFLG7 (13) |
| 14 | QLFLG7 (15) ≤ near-neighbor distance < QLFLG7 (14) |
| 15 | QLFLG7 (16) ≤ near-neighbor distance < QLFLG7 (15) |

**Table - 2e : Quality Flag 7 Definition**

| Flag Value | Definition |
|---|---|
| 0 | near-neighbor distance ≥ QLFLG8 (1) |
| 1 | QLFLG8 (2) ≤ near-neighbor distance < QLFLG8 (1) |
| 2 | QLFLG8 (3) ≤ near-neighbor distance < QLFLG8 (2) |
| 3 | QLFLG8 (4) ≤ near-neighbor distance < QLFLG8 (3) |
| 4 | QLFLG8 (5) ≤ near-neighbor distance < QLFLG8 (4) |
| 5 | QLFLG8 (6) ≤ near-neighbor distance < QLFLG8 (5) |
| 6 | QLFLG8 (7) ≤ near-neighbor distance < QLFLG8 (6) |
| 7 | QLFLG8 (8) ≤ near-neighbor distance < QLFLG8 (7) |
| 8 | QLFLG8 (9) ≤ near-neighbor distance < QLFLG8 (8) |
| 9 | QLFLG8 (10) ≤ near-neighbor distance < QLFLG8 (9) |
| 10 | QLFLG8 (11) ≤ near-neighbor distance < QLFLG8 (10) |
| 11 | QLFLG8 (12) ≤ near-neighbor distance < QLFLG8 (11) |
| 12 | QLFLG8 (13) ≤ near-neighbor distance < QLFLG8 (12) |
| 13 | QLFLG8 (14) ≤ near-neighbor distance < QLFLG8 (13) |
| 14 | QLFLG8 (15) ≤ near-neighbor distance < QLFLG8 (14) |
| 15 | QLFLG8 (16) ≤ near-neighbor distance < QLFLG8 (15) |

**Table - 2e : Quality Flag 8 Definition**